Aquaculture 280 (2008) 94–108

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Energy and resource consumption of land-based Atlantic salmon smolt hatcheries in the Pacific Northwest (USA)

John Colt [a,*], Steve Summerfelt [b], Tim Pfeiffer [c], Sveinung Fivelstad [d], Michael Rust [a]

[a] National Oceanic and Atmospheric Administration, Northwest Fisheries Science Center, Resource Enhancement and Utilization Technologies Division, 2725 Montlake Blvd. East, Seattle, WA 98112, USA

[b] The Conservation Fund's Freshwater Institute, 1098 Turner Road, Shepherdstown, WV 25443, USA

[c] USDA Agricultural Research Service, Sustainable Marine Aquaculture Systems, 5600 U.S. Hwy 1 North, Fort Pierce, FL 34946, USA

[d] Sveinung Fivelstad, Department of Engineering, Bergen College, Nygardsgaten 112, PB 7030, N-5020, Bergen, Norway

ARTICLE INFO

Article history:
Received 19 November 2007
Received in revised form 5 May 2008
Accepted 6 May 2008

Keywords:
Net energy
Sustainability
Greenhouse gas emissions
Energy efficiency

ABSTRACT

This paper evaluates the resource and energy requirements of six different types of land-based, hatchery production systems located in the U.S. Pacific Northwest: flow-through with a gravity water supply, flow-through with a pumped water supply, flow-through with pure oxygen, partial reuse system, partial reuse with heating, and a reuse system for the production of Atlantic salmon (*Salmo salar*) smolts. Key parameters used in the evaluation include direct energy, indirect energy, transportation energy, greenhouse gas emissions, and pollutant discharges.

Power (electricity and natural gas) and feed energy accounted for the majority of the required energy for all the rearing option evaluated. The sum of the fixed capital and chemicals components accounted for less than 2–12% of the total energy budget for any rearing option. The energy efficiency (energy output/energy input) of the six options ranges from 0.97% for flow-through with pumped supply to 3.49% for the flow-through with gravity supply. The rearing options with the three highest energy efficiencies were flow-through with gravity supply (3.49%), partial reuse (2.75%), and reuse (2.64%).

On a kg of smolt produced basis, the six rearing options showed a wide range in performance. The reuse system had the lowest water (2 m^3 kg^{-1}) and land (0.13 m^2 kg^{-1}) requirements and the third lowest total energy requirement (288 MJ kg^{-1}). The partial reuse system had the second lowest total power requirement (276 MJ kg^{-1}), a low land requirement (0.21 m^2 kg^{-1}), and moderate water requirements (33 m^3 kg^{-1}). The partial reuse with temperature control had the second highest total power requirement (657 MJ kg^{-1}) and land and water requirements similar to the partial reuse system without temperature control. The flow-through system with pumped water supply had the highest water (289 m^3 kg^{-1}), land (2.19 m^2 kg^{-1}), and energy requirements (786 MJ kg^{-1}) of any of the rearing options. By comparison, the flow-through system with gravity water supply had the lowest energy requirement (218 MJ kg^{-1}), a moderate land requirement (0.78 m^2 kg^{-1}), and a high water requirement (214 m^3 kg^{-1}). The ranking of the six rearing options based capital and operating costs are likely to be quite different from those based on energy, water, and greenhouse gas emissions.

1. Introduction

Commercial aquacultural production is driven by production costs and economic returns. Conventional economic analysis does not typically include societal costs associated with ecological or environmental impacts and may significantly underestimate production costs and ecosystem impacts. “During the closing decades of the 20th century, concern has grown regarding humanity's impact on the natural environment, or ecosphere, and its capacity, in turn, to continue to meet the resource extraction and waste assimilation needs of a growing human population with rising per capita consumption demands” (Tyedmers, 2000). Sustainable development implies that current demands will not compromise the ability of future generations to meet their own needs (WCED, 1987), and that food production systems should be as efficient as possible and minimize environmental impacts.

While reducing the impact of human activities on the environment is a desirable goal, there does not appear to be a clear and comprehensive definition of what it actually means or how to achieve it on a practical basis. Different production systems will have different labor, energy, and physical components. To compare these systems from a sustainability perspective, it is necessary to be able to evaluate the components of each system in terms of some type of “common currency”.

Two potential analytical tools for sustainability analysis include (a) energy analysis and (b) greenhouse gas emissions. Energy analysis

* Corresponding author. Tel.: +1 206 860 3243.
E-mail address: john.colt@noaa.gov (J. Colt).

0044-8486 Published by Elsevier B.V. Open access under CC BY-NC-ND license.
doi:10.1016/j.aquaculture.2008.05.014

(or net energy analysis) is a form of energy accounting that considers both direct and indirect energy inputs to a given process (Spreng, 1988). Greenhouse gas emissions (carbon dioxide, methane, nitrous oxides, and fluorocarbon) are of current interest because their potential impact on global warming and ocean acidification.

The rapid development of salmon aquaculture "has been accompanied by a growing and vociferous host of criticisms, largely related to the potential impacts of intensive net pens on local ecosystems" (Pelletier and Tyedmers, 2007). Environmental organizations have suggested replacement of net pens with (a) rigid wall floating closed containment systems (Naylor et al., 2003; David W. Ellis and Associates, 1996), (b) land-based flow-through system (Naylor et al., 2003), or (c) reuse or recirculation systems (Goldburg and Triplett, 1997). The potential advantages of these systems are better isolation of the culture fish from wild fish and marine mammals, reduced disease transmission and escapes, and the capture and treatment of fish wastes. While there have been attempts to market fish reared in these systems as "environmentally friendly ecosalmon" (Tyedmers et al., 2007), the energy and resource consumption of these systems have not been clearly documented and compared with existing production systems.

While most of the criticism by environmental groups has been directed at replacement of net pens, the potential use of reuse systems for freshwater smolt production or general aquaculture development has also been advocated (David W. Ellis and Associates, 1996; Goldburg and Triplett, 1997). Proponents of recirculation systems state that "indoor fish production using recirculation aquaculture systems (RAS) is sustainable, infinitely expandable, environmentally compatible, and has the ability to guarantee both the safety and quality of the fish produced throughout the year" (Timmons and Ebeling, 2006). Tyedmers et al. (2007) questioned the sustainability of closed containment and recirculation systems because of the high energy inputs needed for pumping, aeration, and water treatment.

Up to 2008, there are less than 20 published studies on the energy requirements of aquaculture systems and only three that primarily deal with salmonid production systems (Folke, 1988; Pitcher, 1977; Tyedmers, 2000). There are a number of methodological problems and issues encountered in energy studies (Patterson, 1996) and different studies may be based on quite different approaches and assumptions (Spreng, 1988). These problems make it very difficult to directly compare different studies.

The Atlantic salmon is an anadromous fish with maturation, spawning, and early fry development occurring in freshwater. At approximately 60–90 g, Atlantic salmon fingerlings undergoes a physiological transformation called smoltification and can adapt to seawater. Typically at this stage, Atlantic salmon smolts are transferred to marine net pens until harvest. Atlantic salmon eggs are also available almost year round and certified to be free from listed pathogens, which are both important factors that support the widespread production of this species. Atlantic salmon were selected as a model because its production is larger than all other cultured marine fish species (Tucker, 1998) and its production criteria are well documented.

The purpose of this article is to compare the resource and energy consumption of a commercial-sized hatchery (192 MT year^{-1}), using an existing Atlantic salmon (*Salmo salar*) smolt facility as a base case. Six types of production systems are considered: flow-through with gravity water supply (FT-G), flow-through with pumped water supply (FT-P), flow-through with pure oxygen (PO), partial reuse system (PR), partial reuse with heating (PR-T), and a reuse system (RU). These technologies are well developed for commercial fish culture. The key parameters used in the analysis include direct and indirect energy use, greenhouse gas emissions, and pollutant discharges. Clear documentation of the energy and resource consumption of a wide range of production systems will be useful for policy, planning, and regulation of aquaculture development.

2. Background

General information on fish culture performance parameters, energy efficiency parameters, water efficiency and water quality criteria are presented in this section.

2.1. Oxygen and feed measures

$$\mathrm{COC} = \sum_{1}^{n} (\mathrm{DO_{in}} - DO_{out}) \tag{1}$$

$$\mathrm{CFB} = \left[\frac{10^6\ \mathrm{mg/kg} \times M_{ru} \times \mathrm{FR}}{1440\ \mathrm{min/day} \times Q_{mu}}\right] \tag{2}$$

where

COC	Cumulative oxygen consumption (mg O_2 L^{-1})
DO_{out}	Effluent dissolved oxygen from a rearing unit (mg L^{-1})
DO_{in}	Influent dissolved oxygen to a rearing unit (mg L^{-1})
n	Number of rearing units in series
M_{ru}	Mass of fish in rearing units (kg)
FR	Daily feeding rate (kg feed (kg fish day)$^{-1}$)
CFB	Cumulative feed burden (mg feed L^{-1})
Q_{mu}	Make-up flow to system (L min^{-1}).

Cumulative oxygen consumption (Colt and Watten, 1988; Colt and Orwicz, 1991) has been commonly used to characterize intensity in serial reuse systems and cumulative feed burden (Colt et al., 2006) for partial reuse and reuse systems.

2.2. Energy efficiencies

Energy efficiencies (Patterson, 1996) may be defined in terms of enthalpy (Eqs. (3) and (4)) or physical output and enthalpy (Eq. (5)):

$$\text{Energy Efficiency (Enthalpic)} = \left[\frac{\Delta H_{out}}{\Delta H_{in}}\right] 100 \tag{3}$$

$$\text{Input/Output Ratio (Enthalpic)} = \frac{\Delta H_{in}}{\Delta H_{out}} \tag{4}$$

$$\text{Energy Efficiency (physical}-\textit{thermodynanic}) = \frac{\Delta H_{in}}{M_{prod}} \tag{5}$$

where

ΔH_{out}	Heat content or enthalpy of useful outputs (MJ)
ΔH_{in}	Heat content or enthalpy of all inputs (MJ)
M_{prod}	Net mass of fish produced (kg).

Energy efficiency represents the percent of input energy transferred to the useful product and the input/output ration is a measure

Table 1
Summary of water quality criteria used in model

Parameter	Basis	Criterion	Reference
Dissolved oxygen	Reduction in growth	>7.0 mg L^{-1}	Bergheim et al. (2002), Hosfeld et al. (2008)
Carbon dioxide	Increased prevalence of nephrocalcinosis	<10 mg L^{-1}	Akvakulturdriftsforskriften (2004), Fivelstad and Binde (1994), Fivelstad et al. (1999, 2003), Smart et al. (1979)
pH	Reduction in haematocrit after transfer to seawater	>6.0	Fivelstad et al. (2004)
Ammonia	Increase in plasma glucose	<15 μg L^{-1} as NH_3–N	Knoph (1992); Fivelstad et al. (1993), Willingham et al. (1979)
Nitrite	Increase in mortality	<0.1 mg L^{-1} as NO_2^-–N	Colt (2006), Wang et al. (2006)

of the amount of input energy needed to produce a unit output of useful product.

2.3. Water efficiency

$$\text{Water Efficiency} = \left[\frac{W_{total}}{M_{prod}}\right] \quad (6)$$

where

Water Efficiency m^3 water (kg fish produced)$^{-1}$
W_{total} Total water used per cycle (m^3).

2.4. Biological water quality criteria

Water quality criteria for critical parameters determine rearing volume, flowrate, and process treatment performance requirements. The water criteria used in this article are summarized in Table 1.

3. Materials and methods

3.1. Production modeling

The base case for the production modeling is an existing Atlantic salmon smolt facility in the Pacific Northwest. This facility produces 2.4 million 80-g smolts year^{-1} or approximately 192,000 kg year^{-1}. The base case model was calibrated using actual growth and mortality data from this facility. A time interval of one week was used for the model. The specific production model criteria are presented in Table 2.

No broodstock were held onsite; all gametes were transported from a separate facility to the smolt production facility. At the end of the production cycle, smolts were hauled to one or more marine net pen sites.

Table 2
Production criteria for Atlantic smolt production

Parameter	Units	FT-G[a]	FT-P[a]	PO[a]	PR[a]	PR-T[a]	RU[a]
Smolt production goal							
Number	#	2,400,000	2,400,000	2,400,000	2,400,000	2,400,000	2,400,000
Weight	kg	192,000	192,000	192,000	192,000	192,000	192,000
Survival criteria							
Green egg to smolt	%	78	78	78	78	86	86
Rearing units							
Diameter	m	15.0	15.0	15.0	12.2	12.2	15.0
Water depth	m	1.00	1.00	1.00	1.50	1.50	3.00
Density criteria	kg m^{-3}	40	40	40	40	40	40
Production capacity	fish cycle^{-1}	87,532	87,532	87,532	87,532	87,532	262,596
Fish growth							
Initial weight	g	0.2	0.2	0.2	0.2	0.2	0.2
Final weight	g	80	80	80	80	80	80
G_c (Eq. (7))		1.05	1.05	1.05	1.05	1.05	1.05
Feed conversion ratio (FCR)	kg kg^{-1}	1.10	1.10	1.10	1.10	1.10	1.10
Temperature	°C	5–15	10	10	10	16	16
Influent dissolved oxygen	%	100	95	138	115	120	138
Influent alkalinity	mg L^{-1}	100	100	100	100	100	100
Production cycle	d	364	371	371	371	231	231
Production cycles/year	# year^{-1}	1.0	1.0	1.0	1.0	1.6	1.6
Water quality criteria							
Ammonia (NH_3–N)	μg L^{-1}	15	15	15	15	15	15
Nitrite (NO_2–N)	mg L^{-1}	0.1	0.1	0.1	0.1	0.1	0.1
Dissolved oxygen	mg L^{-1}	>7.0	>7.0	>7.0	>7.0	>7.0	>7.0
Carbon dioxide	mg L^{-1}	10	10	10	10	10	10
pH		>6.0	>6.0	>6.0	>6.0	>6.0	>6.0
Ca^{+2}	mg L^{-1}	>20	>20	>20	>20	>20	>20
Soluble pollutional loads							
Solids	kg (kg feed)$^{-1}$	N/A	N/A	N/A	N/A	N/A	N/A
Total nitrogen	kg (kg feed)$^{-1}$	0.034	0.034	0.034	0.034	0.034	0.034
Carbon dioxide	kg (kg feed)$^{-1}$	0.340	0.340	0.340	0.340	0.340	0.340
Total phosphorus	kg (kg feed)$^{-1}$	0.0055	0.0055	0.0055	0.0055	0.0055	0.0055
Fecal pollutional loads							
Solids	kg (kg feed)$^{-1}$	0.265	0.265	0.265	0.265	0.265	0.265
Total nitrogen	kg (kg feed)$^{-1}$	0.007	0.007	0.007	0.007	0.007	0.007
Carbon dioxide	kg (kg feed)$^{-1}$	0.364	0.364	0.364	0.364	0.364	0.364
Total phosphorus	kg (kg feed)$^{-1}$	0.010	0.010	0.010	0.010	0.010	0.010
Transformations (solids→dissolved)							
Solids	%	10	10	10	5	5	3
Total nitrogen	%	50	50	50	15	15	10
Carbon dioxide	%	10	10	10	5	5	3
Total phosphorus	%	40	40	40	15	15	10
Transformations (dissolved→atmosphere)							
Solids	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total nitrogen	%	1	1	1	3	3	5
Carbon dioxide	%	10	10	20	90	90	95
Total phosphorus	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Effluent solids removal	%	60	60	60	80	80	95

[a] FT-G = flow-through with a gravity water supply, FT-P = flow-through with a pumped water supply, PO = flow-through with pure oxygen, PR = partial reuse system, PR-T = partial reuse with heating, and RU = reuse system.

3.2. Growth model

The change in weight over the production cycle was modeled using a simple ΔL model (Iwama, 1996):

$$W_f^{1/3} = W_i^{1/3} + G_c\left[\frac{T}{1000}\right] \times t \quad (7)$$

where

W_f	Final weight (g)
W_i	Initial weight (g)
G_c	Correction factor ($g^{1/3}$ C^{-1} t^{-1})
T	Temperature (°C)
t	Time in days.

A value of G_c = 1.05 was used for all cases. This value was computed from the production duration and water temperature for the base case facility. This value is close to the mean of the G_c value (0.91 ± 0.21) listed in Table 1 in Iwama (1996) for freshwater rearing of salmonids. The length of the production cycle varied from 615 days at 6 °C, to 371 days at 10 °C, and to 231 days at 16 °C.

3.3. Temperature model

In the flow-through system with gravity water supply (FT-G), the ambient water temperature was computed from the relationship developed by Collings (1973):

$$\text{Temperature } (^{o}\text{C}) = 10.0 + 5.0 \sin(0.017 \times \text{JD} + 4.0) \quad (8)$$

where

JD Julian day.

This temperature variation is typical of Western Washington streams, but is not based on a particular stream or river. The groundwater temperature for the other systems was assumed to be a constant 10 °C.

3.4. Mortality model

Mortality over the production cycle was assumed to be linear (Watten, 1992) with $Z = -0.0006739$ day^{-1}. The linear mortality parameter (Z) was computed from actual production information obtained from the base case facility. This resulted in a 78% survival (ponding to smolt transfer) at 10 °C and 86% at 16 °C.

3.5. Flow and volume estimates

Flow across the rearing units was based on oxygen consumption (Liao, 1971) as recomputed by Forsberg (1994) and a minimum DO criterion of 7.00 mg L^{-1}. Maximum density at smolt transfer was based on rearing unit volume (see Table 2) and a density criterion of 40 kg m^{-3}. Based on operational considerations, the flow to each tank was assumed to be constant over the entire production cycle. It was assumed for modeling purposes that swim-ups were stocked directly into the production rearing units. In reality, fish were initially ponded in 1.55-m diameter tanks, and transferred to 3-m, 5-m, 8-m tanks as they grew and finally to the large production tanks (12–15 m).

3.6. Pollutional loads, transformations, and transfer to the atmosphere

The pollutional loads for fecal solids, total nitrogen, carbon dioxide, and total phosphorus were based on a feed basis (Willoughby, 1968). The loadings for soluble wastes were obtained from Clark et al. (1985) for total nitrogen and total phosphorus and from Kutty (1968) for carbon dioxide. The ratios of soluble waste/(soluble + fecal wastes) were obtained from Mente et al. (2006) for total nitrogen, from Buryniuk et al. (2006) for carbon dioxide, and from Bureau and Cho (1999) for total phosphorus. The solids production rate was based on Clark et al. (1985) using data from the 70-g fish.

Using a mass balance approach (Fig. 1; Table 2), the mass of each parameter discharged to the receiving water body (or sewer), collected in the sedimentation pond or solid collection system, and discharged to the atmosphere were estimated. Because of the variable time solids that remained in the sedimentation pond or solids removal treatment systems, the transformation of fecal wastes to soluble wastes was considered (see Table 2). The values of the fecal waste transformation parameters depend very strongly on the design and operation of the solids treatment process. The value of $T_{sol\rightarrow atm}$ for total nitrogen represented the loss of nitrogen by ammonia volatilization or dentrification and the value of $T_{sol\rightarrow atm}$ for carbon dioxide represents gas transferred to the atmosphere. The values of $T_{fecal\rightarrow sol}$ and $T_{sol\rightarrow atm}$ are based on best engineering judgment as there is little data available for these overall system parameters.

3.7. Description of production systems considered

Six different types of production systems were evaluated: flow-through — gravity, flow-through — pumped, pure-oxygen flow-through, partial reuse, partial reuse with temperature control, and reuse. All six of these types of systems are currently being used to rear Atlantic smolts on a commercial scale in different parts of the world. Each assumed production facility has buildings for egg quarantine, incubation and early rearing, equipment storage and repair, feed storage and distribution. The following section presents information on the unique rearing characteristics of each system.

3.7.1. Flow-through systems with gravity water supply (FT-G)

Flow-through systems use water flow to provide oxygen and remove waste products (Colt, 1991; Colt and Tomasso, 2001). The flow-through system with gravity water supply has a simple process flow sheet (Fig. 2). Water is obtained from a surface water supply, degassed in a packed column, passed through a calcium reactor to increase calcium concentration, and then into the rearing unit. A well supply is used for incubation and early rearing up to 5.00-cm length. The effluent water, solids, and dissolved pollutants are passed through a settling pond (2-h detention time) and are discharged to the receiving water body.

To produce the required 2,400,000 smolts, 28 15-m diameter production tanks are needed. There are 1.0 production cycles $year^{-1}$, so 28 batches of smolts are needed. Each rearing tank is single-pass and independent of the rest of the system.

3.7.2. Flow-through systems with pumped water supply (FT-P)

This system is similar to flow-through system with gravity supply except that a pumped well system is used. The process flow sheet and rearing facilities are the same as for the FT-G.

3.7.3. Pure-oxygen flow-through systems (PO)

This type of system is similar to flow-through systems (FT-G and FT-P) with the exception that pure oxygen is used to increase the carrying capacity of the water supply (Colt and Orwicz, 1991, Colt and Watten, 1988). A liquid oxygen (LOX) storage tank, distribution piping, and pure-oxygen contact systems are required (Fig. 2). Because the temperature is the same as for the previous system, numbers of production tanks and production batches are also the same but the overall water flow requirement is significantly reduced.

3.7.4. Partial reuse (PR)

In a partial reuse system, biological ammonia removal is not provided but the un-ionized ammonia concentration is controlled by adjustment

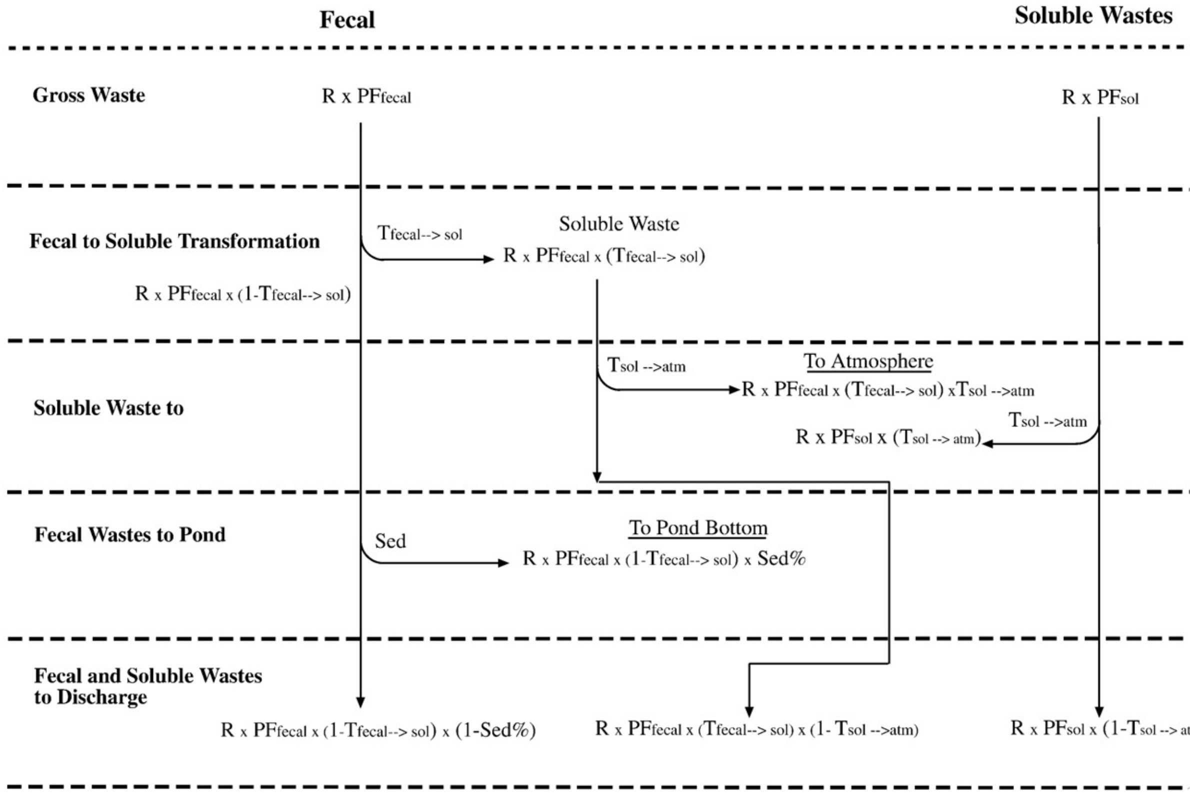

Fig. 1. Mass balance on fecal and soluble wastes for a general parameter "x". The following terminologies are used: R = ration (kg day^{-1}), PF_{fecal} = pollution factor for "x" contained in fecal solids (kg "x" in fecal solids (kg feed)$^{-1}$), PF_{sol} = pollution factor for "x" as a soluble wastes (kg "x" as soluble wastes (kg feed)$^{-1}$), $T_{fecal \rightarrow sol}$ = transformation of solid waste to soluble waste (%), $T_{sol \rightarrow atm}$ = transfer of soluble waste to atmosphere (%), and Sed% = overall systems solids capture (%). Not all atmospheric transfer parameters are defined (see Table 2).

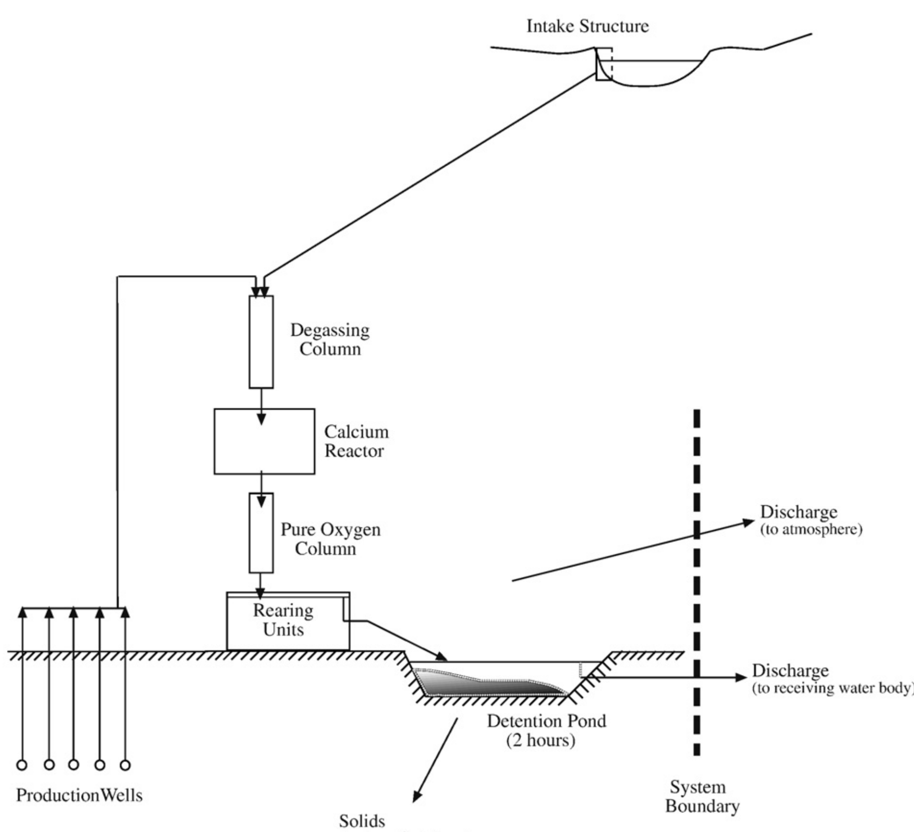

Fig. 2. Process flow sheet for flow-through (FT-G and FT-P) and pure-oxygen (PO) systems for production of Atlantic salmon smolts. The pure-oxygen column is not needed for the two flow-through systems. The flow-through system with pumped supply (FT-P) does not use water from the surface supply.

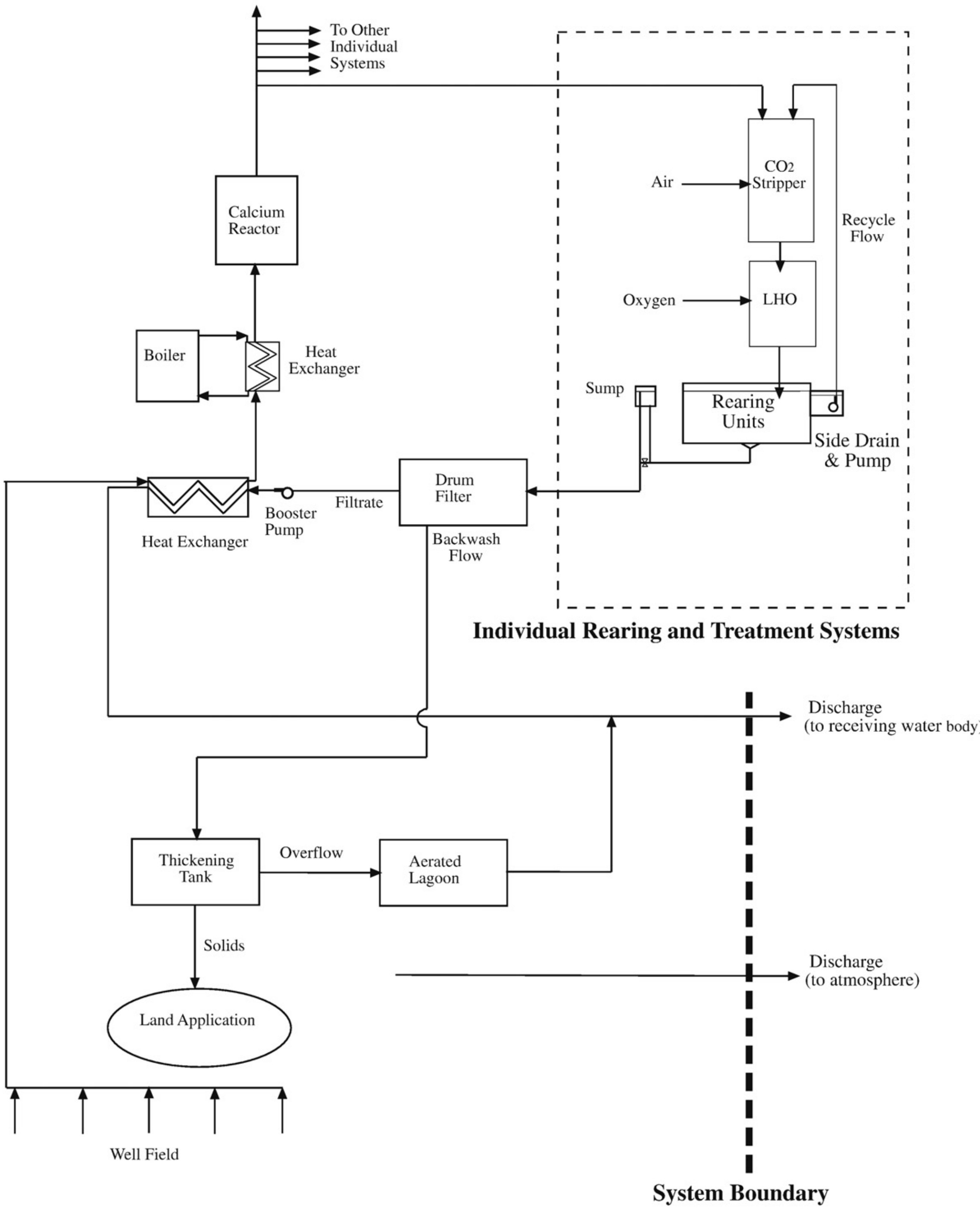

Fig. 3. Process flow sheet for partial reuse (PR) and partial reuse system with temperature control (PR-T) for production of Atlantic salmon smolts. The low-head oxygenator (LHO) is a pure-oxygen transfer system commonly used in salmon and trout facilities. The heat exchanger and booster pump are not needed for the partial reuse system.

of makeup flows, carbon dioxide and pH (Summerfelt et al., 2004). The partial reuse system is a much more complex process flow sheet (Fig. 3). The water leaving the rearing unit can take two routes: side drain and bottom drain. The low solid containing water from the side drain is pumped up to the top of carbon dioxide stripping column and mixed with the make up water before it is treated for reuse. Oxygen supplementation is provided by a low-head oxygenator (LHO™) system (Wagner et al., 1994). The LHO system is a multi-staged oxygen system that has high absorption efficiency at 0.20 to 1.0 m of drop (Watten and Boyd, 1990). The water passes through the carbon dioxide stripper and LHO for oxygen addition and then flows back to the rearing tank. The high solid containing water from the bottom drain from each rearing unit flows through a mort capture/waste feed observation sump and then is combined and treated in a centralized drum filter. The solids captured by the drum filter are discharged to the thickening tank and the effluent filtered water is discharged to the receiving water. The solids discharged to the thickening tank are concentrated for disposal. The overflow water from the thickening tank is discharged to an aerated lagoon for final polishing and discharge to the receiving water. It is assumed that the land for the liquid and solids from the settling tank is onsite.

To produce the required 2,400,000 smolts, 28 12-m diameter production tanks are needed. The rearing tanks for partial reuse system are smaller in diameter (12 m vs. 15 m) but deeper (1.50 m vs. 1.0 m) than the first two systems. The changes in tank geometry were made to improve flow distribution and self-cleaning characteristics of the tanks. There are 1.0 production cycles year^{-1}, so 28 batches of smolts are needed. Each rearing tank is single-pass and independent of the rest of the system.

Due to its relatively high system exchange rate, the partial reuse system can maintain its water temperature at near 10 °C without being installed inside a building in many temperate coastal climates.

3.7.5. Partial reuse with temperature control (PR-T)

Because of reduced water requirements, temperature adjustment is feasible in partial reuse systems (Vinci et al., 2004). This production system is similar to the previously discussed partial reuse system (PR) with the exception of addition of an effluent heat exchanger, booster pump, and natural gas-fired boiler. The 16 °C water being discharged is used to pre-heat the influent water.

It is assumed that this system will be operated at 16 °C. Increasing the temperature from 10 °C to 16 °C, reduces the production cycle from 371 days to 231 days and each physical tank can produce 1.6 batches year^{-1}. Therefore, only 18 physical production tanks are needed to produce 28 production batches.

3.7.6. Reuse

A reuse system uses a biological filter to control total ammonia and un-ionized ammonia. Other unit processes include aeration, degassing,

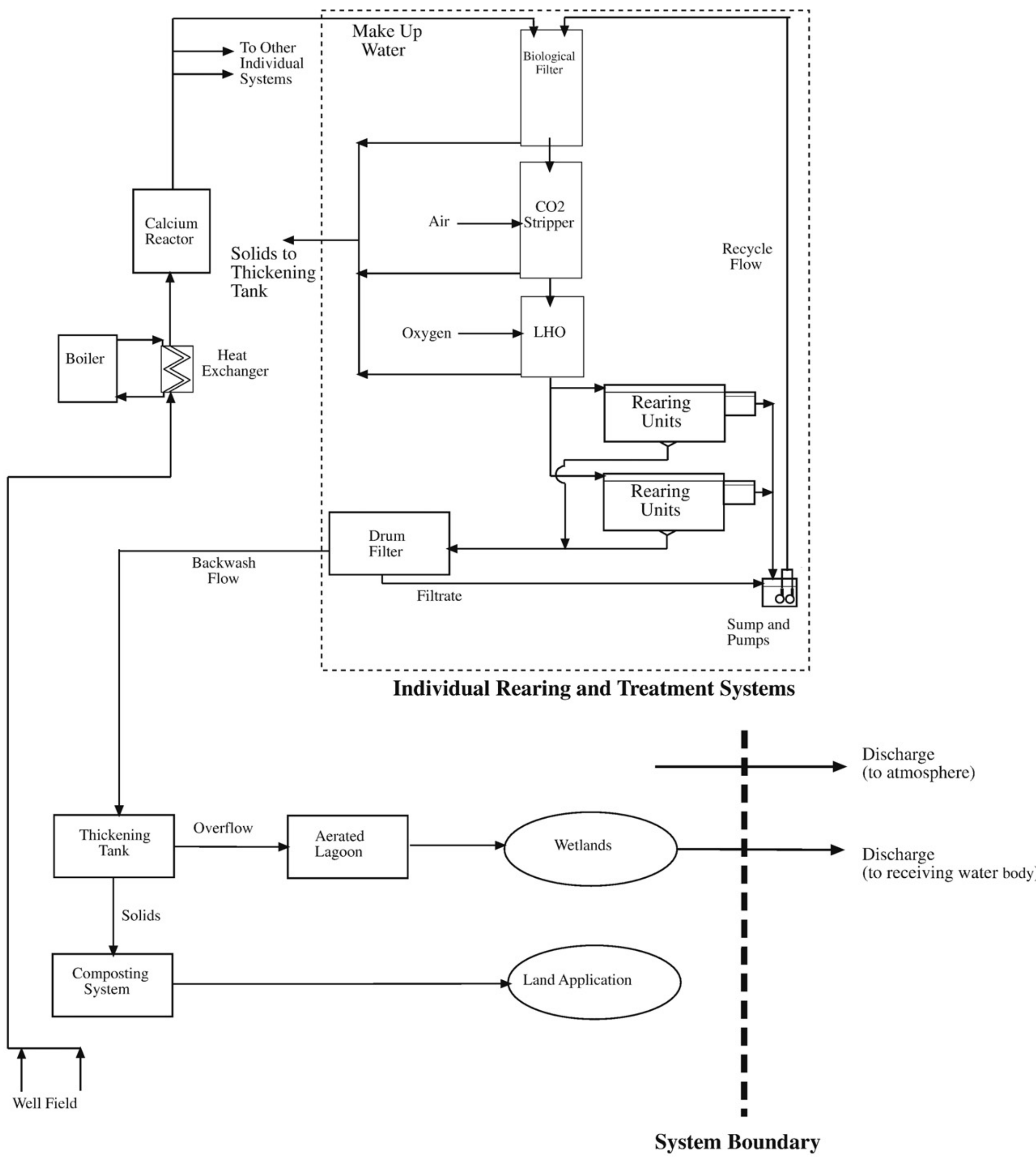

Fig. 4. Process flow sheet for reuse system for production of Atlantic salmon smolts.

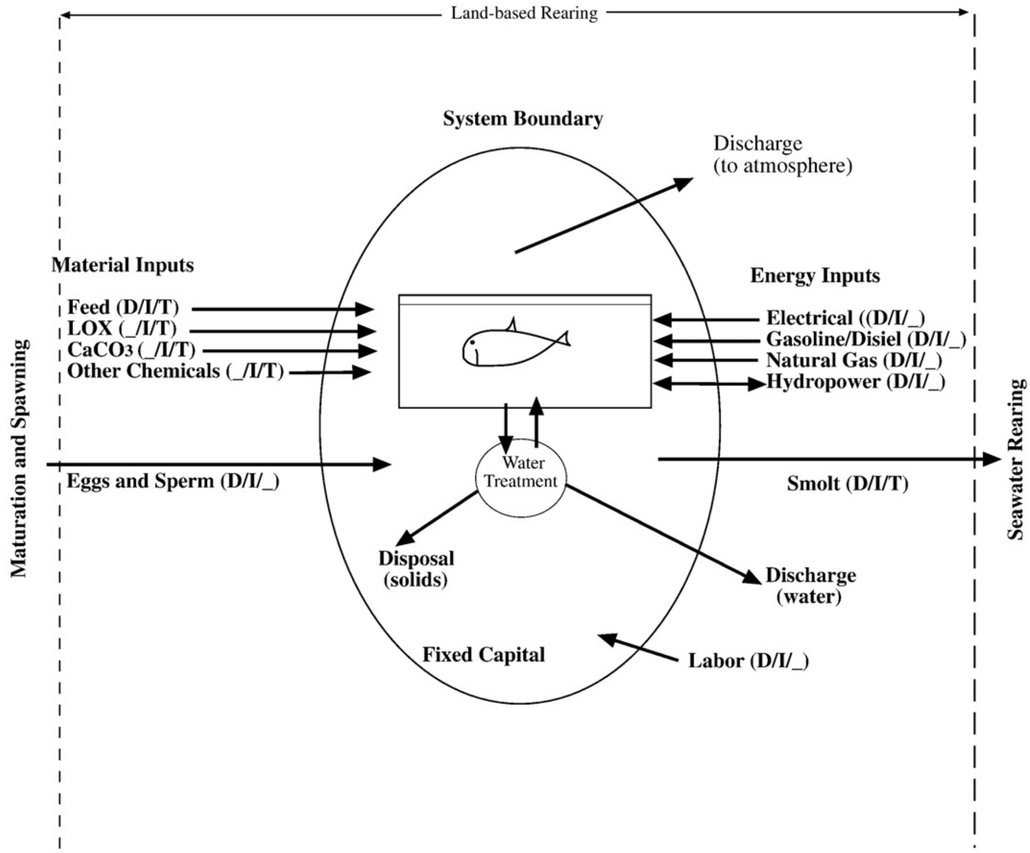

Fig. 5. System boundary and components for energy, resource, and greenhouse gas analysis for land-based Atlantic salmon production system (*D* = direct energy, *I* = indirect energy, and *T* = transportation energy).

pure-oxygen addition, pH adjustment, temperature control, solids removal, and disinfection (Losordo et al., 1998; Summerfelt et al., 2001). The reuse system (Fig. 4) has the most complex process flow sheet to allow for nearly complete environmental control. The discharge from the rearing tanks passes through a drum filter to remove solids. The effluent from the drum filter is pumped through a fluidized bed sand filter to remove ammonia and dissolved organics; this water then flows by gravity down through a carbon dioxide stripping column, a LHO to add dissolved oxygen, and then back to the rearing units. The settled solids from the drum filter, fluidized bed sand filter, carbon dioxide stripper, and LHO are discharged into a thickening tank. The settled solids are composted and disposed of. The liquid from the settling tank is aerated and discharged into wetlands. It is assumed that the land for the liquid and solids from the settling tank is onsite.

It is assumed that this system is operated at 16 °C. The volume of each rearing tank used for the reuse system is 3 times larger than the other systems (525 m^3); thus, only 6 rearing tanks are needed to meet the production goals. The increase in individual tank volume is a result

Table 3
Resource and energy requirements for the six production options

	Units	FT-G	FT-P	PO	PR	PR-T	RU	Useful life (year)	Transport (km)
Inputs									
Eggs	kg	480	480	480	480	436	436		
Feed	kg year^{-1}	218,120	218,120	218,120	218,120	218,120	218,120		150
Power									
Electricity	kW h year^{-1}	1,191,000	11,975,000	5,694,000	3,267,000	2,917,000	3,004,000		
Gasoline	L year^{-1}	0	0	0	0	0	0		
Diesel	L year^{-1}	0	0	0	0	0	0		
Natural gas	L year^{-1}	0	0	0	0	1,661,795,407	108,376,827		
Hydropower	kW h year^{-1}	876,000	0	0	0	0	0		
Labor	FTE	12	12	12	13	13	14		
Fixed capital									
Steel	kg	102,000	121,000	108,000	108,000	108,000	251,000	15	
Aluminum	kg	10,000	19,000	20,000	12,000	12,000	12,000	15	
Fiberglass/plastic	kg	157,000	202,000	153,000	129,000	108,500	139,000	15	
Concrete	kg	2,644,000	1,944,000	1,944,000	1,635,000	1,247,000	2,283,000	20	
Calcium carbonate	kg year^{-1}	1,618,000	2,190,000	951,000	251,000	242,000	59,000		600
LOX	kg year^{-1}	0	0	104,000	1,500	25,000	159,000		90
Smolts	kg year^{-1}	192,000	192,000	192,000	192,000	192,000	192,000		120
Outputs									
Smolts	kg year^{-1}	192,000	192,000	192,000	192,000	192,000	192,000		

Table 4a
Primary, secondary, and transportation energy requirements for flow-through with gravity supply (FT-G) land-based hatchery system

	Component	Energy (MJ year^{-1})			
		Direct energy	Indirect energy	Transport energy	Total energy
Input	Eggs	3600			3600
	Feed	4,881,526	10,487,210	65,927	15,434,662
	Electricity	12,255,390	738,420		12,993,810
	Natural gas				
	Hydropower	9,014,040	543,120		9,557,160
	Steel		170,000		170,000
	Aluminum		93,333		93,333
	Fiberglass/plastic		785,000		785,000
	Concrete		132,200		132,200
	Calcium carbonate		74,428	1,956,162	2,030,590
	LOX				
	Smolts			568,714	568,714
	Total (input)	26,154,556	13,023,711	2,590,802	41,769,069
Output	Smolts	1,459,200			

Table 4b
Primary, secondary, and transportation energy requirements for flow-through with pumped supply (FT-P) land-based hatchery system

	Component	Energy (MJ year^{-1})			
		Direct energy	Indirect energy	Transport energy	Total energy
Input	Eggs	3600			3600
	Feed	4,881,526	10,487,210	65,927	15,434,662
	Electricity	123,222,750	7,424,500		130,647,250
	Natural gas				
	Hydropower				
	Steel		201,667		201,667
	Aluminum		177,333		177,333
	Fiberglass/plastic		1,010,000		1,010,000
	Concrete		97,200		97,200
	Calcium carbonate		100,740	2,647,710	2,748,450
	LOX				
	Smolts			568,714	568,714
	Total (input)	128,107,876	19,498,650	3,282,350	150,888,876
Output	Smolts	1,459,200			

of increasing the water depth from 1.0 m to 3.0 m. The rearing and treatment systems are enclosed in an insulated steel building. The primary reason for increasing the individual rearing tank volume is to decrease building footprint, capital costs, heat transfer losses. A separate treatment system is required for each two rearing tanks. Because of the lower water requirements, site location for this type of system is much easier than for other systems.

3.8. Energy analysis

An energy balance for a smolt production system is presented in Fig. 5. The major inputs are material inputs (feed, pure oxygen, calcium carbonate), energy inputs (electrical, gasoline/diesel, and natural gas), labor, and gametes (eggs and sperm). The major outputs are smolts and waste discharges (water and solids). Fixed capital components such as concrete, steel, aluminum, fiberglass, and plastics in the hatchery facility were considered.

Each input or output may have three types of associated energy: direct energy, indirect energy, and transportation energy. Direct energy is the amount of heat (ΔH) that is released if the compound is burned in a bomb calorimeter. Indirect energy is the amount of energy that was needed to produce a unit weight of a given compound or component. In many cases, the indirect energy inputs are larger than the direct energy contribution. The transportation energy is the energy required to transport material to and from the facility.

Energy analysis is based on estimation of energy density (MJ kg^{-1}, MJ L^{-1}, or MJ (kW h)$^{-1}$) and the mass (kg, liter, or kW h) of the compound or component. The annual energy consumption for a given component may be expressed in MJ year^{-1} (10^6 J year^{-1}) or TJ year^{-1} (10^{12} J year^{-1}). The duration of a single production cycle ranges from 231 to 371 days (Table 2). The number of rearing units was adjusted to produce 192,000 kg year^{-1}. Summary results are therefore expressed per year instead of per production cycle.

The energy densities used in this article are based largely on Tyedmers (2000) and are listed in Appendix A, Table 1. This work compared energy and resources used by net pen aquaculture and capture fishery in British Columbia, only about 300 km to the north of the assumed site in the State of Washington. The appropriateness of these energy density numbers for other locations in the U.S. or other parts of the world was not been evaluated.

Additional energy density information was obtained for liquid oxygen (Brown et al., 1985), indirect energy for fuels (Spreng, 1988), and for salmon eggs (Brafield, 1985; Jonsson et al., 1997). Because of uncertainties in the computation of energy contribution of labor (Troell et al., 2004) and typically small contribution compared to other components, we have elected to not to include this component in our analysis. To adjust for energy quality (Patterson, 1996), electrical energy was expressed in fossil fuel equivalents (Tyedmers, 2000) based on a 35% fossil fuel to electricity conversion (1 kW h = 3.6 MJ, so

Table 4c
Primary, secondary, and transportation energy requirements for pure-oxygen (PO) land-based hatchery system

	Component	Energy (MJ year^{-1})			
		Direct energy	Indirect energy	Transport energy	Total energy
Input	Eggs	3600			3600
	Feed	4,881,526	10,487,210	65,927	15,434,662
	Electricity	58,591,260	3,530,280		62,121,540
	Natural gas				
	Hydropower				
	Steel		180,000		180,000
	Aluminum		186,667		186,667
	Fiberglass/plastic		765,000		765,000
	Concrete		97,200		97,200
	Calcium carbonate		43,746	1,149,759	1,193,505
	LOX		24,960	18,860	43,820
	Smolts			568,714	568,714
	Total (input)	63,476,386	15,315,062	1,803,260	80,594,708
Output	Smolts	1,459,200			

Table 4d
Primary, secondary, and transportation energy requirements for partial reuse (PR) land-based hatchery system

	Component	Energy (MJ year^{-1})			
		Direct energy	Indirect energy	Transport energy	Total energy
Input	Eggs	3600			3600
	Feed	4,881,526	10,487,210	65,927	15,434,662
	Electricity	33,617,430	2,025,540		35,642,970
	Natural gas				
	Hydropower				
	Steel		180,000		180,000
	Aluminum		112,000		112,000
	Fiberglass/plastic		645,000		645,000
	Concrete		81,750		81,750
	Calcium carbonate		11,546	303,459	315,005
	LOX		360	272	632
	Smolts			568,714	568,714
	Total (input)	38,502,556	13,543,406	938,371	52,984,333
Output	Smolts	1,459,200			

Table 4e
Primary, secondary, and transportation energy requirements for partial reuse with temperature control (PR-T) land-based hatchery system

	Component	Energy (MJ year^{-1})			
		Direct energy	Indirect energy	Transport energy	Total energy
Input	Eggs	3270			3270
	Feed	4,881,526	10,487,210	65,927	15,434,662
	Electricity	30,015,930	1,808,540		31,824,470
	Natural gas	63,680,000	13,377,453		77,057,453
	Hydropower				
	Steel		180,000		180,000
	Aluminum		112,000		112,000
	Fiberglass/plastic		542,515		542,515
	Concrete		62,350		62,350
	Calcium carbonate		11,132	292,578	303,710
	LOX		6000	4534	10,534
	Smolts			568,714	568,714
	Total (input)	98,580,726	26,587,200	931,752	126,099,677
Output	Smolts	1,459,200			

Table 4f
Primary, secondary, and transportation energy requirements for reuse with temperature control (RU) land-based hatchery system

	Component	Energy (MJ year^{-1})			
		Direct energy	Indirect energy	Transport energy	Total energy
Input	Eggs	3270			3270
	Feed	4,881,526	10,487,210	65,927	15,434,662
	Electricity	30,911,160	1,862,480		32,773,640
	Natural gas	4,153,000	872,433		5,025,433
	Hydropower				
	Steel		418,333		418,333
	Aluminum		112,000		112,000
	Fiberglass/plastic		695,000		695,000
	Concrete		114,150		114,150
	Calcium carbonate		2,714	71,331	74,045
	LOX		38,160	28,835	66,995
	Smolts			568,714	568,714
	Total (input)	39,948,956	14,602,480	734,806	55,286,242
Output	Smolts	1,459,200			

1 kW h (fossil fuel)=3.6/0.35=10.29 MJ (kW h)$^{-1}$). Some of the criticisms of the use of thermal or fossil fuel equivalents (Patterson, 1993), may not be as important for the relative simple energy input and outputs systems considered in this article.

For the flow-through system with gravity supply, power for the water supply was computed assuming a turbine efficiency of 85% and a drop of 7 m. This power represents the forgone power that could have been recovered using a low-head turbine system for the hatchery flow and 7-m drop.

For each production system, an inventory of the physical components (fixed capital) needed, estimated weight, and percent composition (concrete, steel, aluminum, and fiberglass/plastic) was prepared. A useful life of 20 years was assumed for concrete and 15 years for the other components. The yearly contribution of energy from the fixed capital components was computed from the weight of materials, energy density values (Table 3), and useful life values.

The heat requirement for the partial reuse with temperature control (PR-T) system was computed based on the assumption of recovering 66% of energy in the discharge by a heat exchanger (personal communication, KC Hosler) and use of a natural gas-fired boiler (efficiency=95%). The resulting energy requirement was increased by 15% to account for energy losses from the water to the atmosphere.

Because of greatly reduced water use in the reuse system and reduced heat loss due to use of an insulated building, it was assumed that no additional energy was needed to heat the makeup water. The heat loss from the system was assumed to be equal to 50% of the value used for the partial reuse PR-T system.

The energy required for the final disposals of collected solids was not considered as it is likely to be minor. In rural areas, land disposal on agricultural land is the preferred alternative (Mudrak, 1981); in more urban area, this material can be given away for gardening applications. Any energy use for final disposal of these solids may also be off-set by the energy saved by recycling a waste instead of using newly manufactured products.

3.9. Greenhouse gas emissions

Greenhouse gas emission factors are based largely on Tyedmers (2000) and are presented in Appendix A, Table 2. Emission factors for calcium carbonate (oyster shell) and LOX were based on the energy densities in Appendix A, Table 1 and the assumption that all processing energy was based on electrical energy. The contribution of carbon dioxide from the Atlantic salmon was based on the total feed consumed by the fish and pollution loads and transformations presented in Table 2. The 90% hydropower and 10% natural gas source of electricity (Tyedmers, 2000) is reasonable for the U.S. Pacific Northwest. This assumption may not be appropriate for other parts of the U.S. (or other parts of the world) and could significantly alter the greenhouse emissions characteristics for systems operating outside of

Table 5
Comparison of energy usage for the rearing systems

Parameter	Units	FT-G	FT-P	PO	PR	PR-T	RU
Energy use in absolute units							
Feed	MJ year^{-1}	15,434,662	15,434,662	15,434,662	15,434,662	15,434,662	15,434,662
Electrical/fuel energy	MJ year^{-1}	22,550,970	130,647,250	62,121,540	35,642,970	108,881,923	37,799,073
Fixed Capital	MJ year^{-1}	1,180,533	1,486,200	1,228,867	1,018,750	896,865	1,339,483
Chemicals	MJ year^{-1}	2,030,590	2,748,450	1,237,325	315,637	314,244	141,040
Total energy (all)	MJ year^{-1}	41,769,069	150,888,876	80,594,708	52,984,333	126,099,677	55,286,242
Total of above 4 items	MJ year^{-1}	41,196,755	150,316,562	80,022,394	52,412,019	125,527,694	54,714,258
Total of feed and energy	MJ year^{-1}	37,985,632	146,081,912	77,556,202	51,077,632	124,316,585	53,233,735
Energy use as percentages							
Feed	%	37%	10%	19%	29%	12%	28%
Electrical/fuel energy	%	54%	87%	77%	67%	86%	68%
Fixed Capital	%	3%	1%	2%	2%	1%	2%
Chemicals	%	5%	2%	2%	1%	0%	0%
Total energy (all)	%	100%	100%	100%	100%	100%	100%
Total of above 4 items	%	99%	100%	99%	99%	100%	99%
Total of feed and energy	%	91%	97%	96%	96%	99%	96%

Table 6
Greenhouse gas emissions for six rearing options (MT $year^{-1}$)

Component	Rearing system					
	FT-G	FT-P	PO	PR	PR-T	RU
Feed	725	725	725	725	725	725
Electricity	347	3488	1659	952	850	875
Natural gas	0	0	0	0	4462	291
Labor	0	0	0	0	0	0
Hydropower	0	0	0	0	0	0
Steel	17	20	18	18	18	42
Aluminum	5	10	11	6	6	6
Fiberglass/plastic	31	40	31	26	22	28
Concrete	20	15	15	12	9	17
Calcium carbonate	0.6	0.7	0.3	0.1	0.1	0.0
LOX	0	0	0.2	0.0	0.0	0.3
Transportation	228	289	159	82	82	65
Fish	7	7	15	67	66	71
Total	1381	4595	2632	1839	6240	2121

this region. Greenhouse gas emissions are expressed in g $year^{-1}$ or MT $year^{-1}$ (1000 kg $year^{-1}$).

3.10. Pollution discharges

The wastes produced by the fish were partitioned into (a) the mass discharged to the receiving water (or sewer), (b) the mass collected in the sedimentation pond or solid collection system, and (c) the mass discharged to the atmosphere (see Section 3.6). It is assumed that collected solids are disposed of in an environmentally responsible manner and do not contribution to water pollution.

4. Results

4.1. Energy analysis

The basic resource data used in this analysis is presented in Table 2 and energy density information contained in Appendix A, Table 1. The energy requirements for each rearing system are presented in a separate table: Table 4a — flow-through with gravity supply, Table 4b — flow-through with pumped supply, Table 4c — pure oxygen, Table 4d — partial reuse, Table 4e — partial reuse with temperature control, and Table 4f — reuse.

Tables 4a to 4f, the annual energy requirements in megajoules (MJ) are presented in terms of direct energy, indirect energy, and transportation energy. The direct energy contained in the smolts is the same for all systems and equal to 1,492,000 MJ $year^{-1}$ or 1.492 TJ $year^{-1}$. The total annual energy requirements for the six systems varied from a minimum of 42 TJ (flow-through with gravity supply), 53 TJ (partial reuse), 55 TJ (reuse), to 81 TJ (pure oxygen), to 126 TJ (partial reuse with temperature control), to a maximum value of 151 TJ (flow-through with pumped supply). The total energy requirements for the six systems varied by a factor of 3.6 times.

The annual energy consumption of the six systems are summarized in Table 5 in terms of feed, electric/fuel, fixed capital, and

Table 7
Performance of rearing options

Parameter	Units	FT-G	FT-P	PO	PR	PR-T	RU
Fish culture intensity							
COC (Eq. (1))	mg L^{-1}	4.29	3.72	8.58	4.29	4.84	6.62
CFB (Eq. (2))	mg L^{-1}	15.6	9.29	21.4	893	256	10,100
Total resource consumption							
Water	m^3 $year^{-1}$	40,997,000	55,472,000	24,081,000	6,358,000	6,130,000	362,000
Feed	kg $year^{-1}$	218,109	218,109	218,109	218,109	218,109	218,109
$CaCO_3$	kg $year^{-1}$	1,618,000	2,189,000	951,000	251,000	242,000	59,000
LOX	kg $year^{-1}$	0	0	104,000	1500	25,000	159,000
Direct energy	MJ $year^{-1}$	26,155,000	128,107,000	63,476,000	38,503,000	98,581,000	39,948,000
Indirect energy	MJ $year^{-1}$	13,024,000	19,499,000	15,315,000	13,543,000	26,587,000	14,602,000
Total energy	MJ $year^{-1}$	41,769,000	150,889,000	80,595,000	52,984,000	126,100,000	55,286,000
Electrical/fuel energy	MJ $year^{-1}$	22,551,000	130,647,000	62,122,000	35,643,000	108,881,000	37,798,000
Land Requirement	m^2	150,000	420,000	210,000	40,000	40,000	25,000
Total pollutants (water)							
Solids	kg $year^{-1}$	20,435	20,808	20,808	10,981	10,890	2841
Carbon dioxide	kg $year^{-1}$	100,632	102,468	94,258	60,355	22,706	7784
Total nitrogen (N)	kg $year^{-1}$	8252	8403	8403	7675	7611	7358
Total phosphorus (P)	kg $year^{-1}$	2522	2568	2568	1883	1868	1530
Total pollutants (atm)							
Carbon dioxide (fish)	kg $year^{-1}$	7283	7416	14,831	66,738	66,186	71,410
Total greenhouse gas	kg $year^{-1}$	1,381,000	4,595,000	2,632,000	1,839,000	6,240,000	2,121,000
Unit consumption							
Water	m^3 kg^{-1}	214	289	125	33	32	2
Feed	kg kg^{-1}	1.10	1.10	1.10	1.10	1.10	1.10
$CaCO_3$	kg kg^{-1}	8	11	5	1	1	0.31
LOX	kg kg^{-1}	0	0	0.54	0.01	0.13	0.83
Primary energy	MJ kg^{-1}	136	667	331	201	513	208
Secondary energy	MJ kg^{-1}	68	102	80	71	138	76
Total energy	MJ kg^{-1}	218	786	420	276	657	288
Electrical/fuel energy	MJ kg^{-1}	117	642	324	186	567	197
Land requirements	m^2 kg^{-1}	0.78	2.19	1.09	0.21	0.21	0.13
Unit pollutants (water)							
Solids	kg kg^{-1}	0.11	0.11	0.11	0.06	0.06	0.01
Carbon dioxide	kg kg^{-1}	0.52	0.53	0.49	0.31	0.12	0.04
Total nitrogen (N)	kg kg^{-1}	0.043	0.044	0.044	0.040	0.040	0.038
Total phosphorus (P)	kg kg^{-1}	0.0131	0.0134	0.0134	0.0098	0.0097	0.0080
Unit pollutants (atm)							
Carbon dioxide (fish)	kg kg^{-1}	0.038	0.039	0.077	0.348	0.345	0.372
Total greenhouse gas	kg kg^{-1}	7.19	23.93	13.71	9.58	32.50	11.05
Energy efficiency							
$Energy_{out}/Energy_{in}$	%	3.49	0.97%	1.81%	2.75%	1.16%	2.64%
$Energy_{in}/Energy_{out}$	MJ MJ^{-1}	29	103	55	36	86	38

chemicals. Electrical/fuel energy is the largest single component in all of the 6 rearing systems. The sum of feed energy+electrical/fuel energy accounts for 91 to 99% of the total energy use (Table 5). The sum of feed+electric/fuel+fixed capital+chemicals accounts for 99 to 100% of the total energy use. The absolute energy in transportation, fixed capital, chemicals, and feed were relatively constant; their percent of the total energy budget were driven primarily by the variation in the overall energy budget.

4.2. Greenhouse gas emissions

The total annual greenhouse gas emissions (Table 6) for the six systems varied from: 1381 MT (FT-G), 1839 MT (PR) 2121 MT (RU), to 2632 MT (PO), to 4595 MT (FT-P), to maximum of 6240 MT (PR-T). The greenhouse gas emissions for the six systems varied by a factor of 4.5 times.

The two largest components of greenhouse emissions were power (electrical+fossil fuel) and feed. Feed was the largest component (53%) for FT-G and power was the largest component (50–85%) for all the other systems. Power and feed accounted for 78 to 97% of the total emissions. The respiratory carbon dioxide contribution accounted for only 0.16% to 3.53% of the annual emissions.

4.3. System performance

Overall resource and energy consumption data for the six systems is presented in Table 7. The cumulative oxygen consumption (Eq. (1)) ranged from 3.72 mg L^{-1} for the flow-through system to 8.58 mg L^{-1} for the pure-oxygen system. The cumulative feed burden (Eq. (2)) ranged from 9.29 mg L^{-1} for the flow-through system to 10,100 mg L^{-1} for the reuse system (a factor of approximately 1000 times).

The annual water usage ranged from 362,000 m^3 (RU) to 55,472,000 m^3 (FT-P). Because of a fixed feed conversion ratio and production goal, the feed consumption was the same for all six systems.

Less solids, carbon dioxide, total nitrogen, and phosphorus were discharged in the water from the partial reuse and reuse systems compared to the flow-through and pure-oxygen flow-though systems. More of the respiratory carbon dioxide was discharged into the atmosphere from the partial reuse and reuse systems because of reduced discharges and higher levels of treatment.

The performance of the six systems are summarized below in terms of a kg of annual smolt production:

Parameter	FT-G	FT-P	PO	PR	PR-T	RU
Water usage (m^3 kg^{-1})	214	289	125	33	32	2
Feed (kg kg^{-1})	1.10	1.10	1.10	1.10	1.10	1.10
Electricity and fuel energy (MJ kg^{-1})	117	680	324	186	567	197
Total energy efficiency (MJ MJ^{-1}, %)	3.49	0.97	1.81	2.75	1.16	2.64
Greenhouse gas emissions (kg kg^{-1})	7	24	14	10	33	11

The flow-through system with gravity supply (FT-G) has the lowest energy consumption and the second highest water usage. The reuse (RU) system has the lowest water usage and the third lowest total energy consumption. The flow-through with pumped supply (FT-P) and partial reuse with temperature control (PR-T) have high energy consumptions and widely different water usages.

5. Discussion

5.1. Feed energy

Previous analysis of aquaculture production systems has shown that feed production accounts for the majority of energy and greenhouse gas impacts (Pelletier and Tyedmers, 2007). In this current study, electrical/fuel energy was the largest energy use. The amount of energy in the feed was constant for all the systems and equal to 15 TW $year^{-1}$. Increasing energy use for pumping, aeration, and water treatment reduces the impact from feed production on a percentage basic but has no impact on the absolute value. Life cycle assessment of a recirculating turbot facility in France has also shown that the largest environmental impacts are due to onsite energy use (Aubin et al., 2006).

The energy density of feed might be reduced by use of more efficient fishing practices, improved processing and transportation, and substitution of plant materials for animal products (Pelletier and Tyedmers, 2007). Improvements in the energy densities of the feeds are not under the direct control of the fish farmers. Changes in diets that result in decreased FCRs or increases in price are likely to not be commercially viable.

5.2. Electrical and fuel energy

In contrast to the energy use embodied in feed, the use of electrical and fuel energy is under the direct control of the facility. The largest single component of energy is for electrical power and natural gas. Electrical energy is used for pumping of water, water treatment, and hatchery use (lighting, HVAC, and other hatchery functions):

Energy component	Annual energy use (TJ)					
	FT-G	FT-P	PO	PR	PR-T	RU
Electrical inputs						
Water supply (well pumps)	3	121	53	14	13	1
Internal hatchery uses	10	10	10	10	10	10
Water treatment	0	0	0	12	9	22
Natural gas	0	0	0	0	77	5
Hydropower	10	0	0	0	0	0
Total electrical/fuel energy inputs	23	131	62	36	109	38

5.2.1. Distribution of electrical and fuel use

Typically, the largest power components are influent pumping, heating, and water treatment, although the ranking varies between the systems. The flow-through system with gravity supply (FT-G), has quite different energy consumption characteristics. Because of significantly lower total energy consumption, the two largest power components for this system are internal hatchery use and forgone hydropower generation. The energy required for influent water pumping significantly decreases as the intensity of the culture system increases (FT-P to RU). Energy requirements for water treatment are highest for the reuse system (RU) followed by the partial reuse systems (PR). A significant amount of energy is used for heating process water in the partial reuse system with temperature control (PR-T) and smaller amount for the reuse system (RU).

5.2.2. Impact of temperature control on energy usage

The ability to control water temperature in the partial reuse with temperature control and reuse systems, significantly reduced length of the production cycle from 371 to 231 days (40% reduction). This changes results in reducing the number of production units from 28 to 18 (35% reduction) for partial reuse temperature control (PR-T) system and from 10 to 6 (40% reduction) for the reuse (RU) systems and significantly reduces the footprint of the hatchery area, energy associated with treatment processes, and energy requirements for water treatment. While temperature control had a beneficial impact on production duration, it also increased the total energy consumption of this option from 36 TJ $year^{-1}$ to 109 TJ $year^{-1}$, a factor of 3 times. The heating requirement for the reuse option was significantly smaller than for the heated partial reuse option and accounted for about 13% of the total energy budget. The energy requirements for controlling temperature control in systems are based on the use of a high efficiency (95%) natural gas fueled-boiler and heat exchanger for energy recovery. It may be possible to reduce the energy requirements for temperature control by use of a water–water heat pump.

5.2.3. Influent pumping energy

Influent pumping energy is the single highest component for the flow-through with pumped supply (FT-P) and pure-oxygen systems (PO). The flow-through with gravity supply (FT-G) and reuse (RU) systems have the lowest influent pumping requirements because of greatly reduced groundwater requirements. For a given flow, the energy requirement for pumping depends strongly on the aquifer transmissibility and the resulting groundwater water levels.

Groundwaters are preferred for incubation and early rearing because they are commonly assumed to be disease-free and have a constant temperature (Colt and Tomasso, 2001). Gravity flow from springs or surfaces water are desirable for hatcheries because of greater reliability and the lack of pumps.

While the flow-through system with gravity flow (FT-G) has the lowest total energy requirement, it also has the most restrictive siting requirements:

(1) Availability of 1000 L/s (16,000 gal/min) over the whole year.
(2) Ability to obtain the water right to this water.
(3) Available head of 7 m.
(4) Seasonal temperature range of 5 to 15 °C.
(5) Lack of significant disease organisms in the water.
(6) Acceptable water quality.

It many areas, water supplies with these characteristics are not available at any price. High sediment loads, pathogen or parasite problems, or excessive temperatures may significantly increase the water treatment costs and energy consumption of systems using gravity water supplies. The siting of a pumped system can be significantly easier if groundwater is not limited.

The inclusion of the foregone hydropower power in the FT-G option is justified because the construction of the hatchery precludes hydropower generation at the site. It is important to note that inclusion of this component is equivalent to assuming a pumped system with very high groundwater (7 m of total head).

5.2.4. Impacts of treatment configurations

The partial reuse (PR) and partial reuse with temperature control (PR-T) are based on 28 and 18 independent treatment systems. In contrast, the reuse option is based on only 6 tanks and 3 treatment systems. Water treatment costs (USEPA, 1998) are typically found to be a power function of flowrate:

$$\text{Costs} = aQ^b \tag{9}$$

where

a	constant equal to the cost of a system for Q=1 $m^3\ s^{-1}$
Q	flowrate ($m^3\ s^{-1}$)
b	exponent.

The value of b in Eq. (9) typically ranges from 0.4 to 0.8 depending on the type of system. In terms of cost/unit flow, Eq. (9) can be written as aQ^{b-1}. For any $b \leq 1$, the cost/unit flow decreases with increase flow. For example, for b=0.7, a reduction in the number of independent treatment systems for partial reuse from 28 to 4 and 18 to 3 would reduce capital costs, by a factor of 2.

A treatment system for a single tank must be sized for the maximum biomass. A combined treatment system for 6–7 rearing units can sized for treatment of only 50% of the maximum individual tank biomass because not all of the combined tanks will have the contain maximum biomass at the same time (Watten, 1992). Therefore, the overall capital costs for the combined system may be in the range of 30–40% of the individual systems. While centralization of treatment may offer significant capital and operating cost savings, biosecurity and reliability risks are significantly higher for this approach. The loss of the fish from 1 out 28 rearing tanks is quite different from the equivalent loss of 7 tanks. These potential changes will have a negligible impact on total system energy consumption because of the small contribution of fixed capital to the overall energy budget (Tables 4a to 4f).

Potential risks from equipment failure would be higher for this type of combined treatment configuration and require more backup systems for key components and a comprehensive monitoring and control systems. Biological risk from disease would also be higher for this configuration. The cost and energy saving would have to balanced against the increased biological risks.

5.3. Overall energy efficiencies

In the evaluation of energy usage in aquaculture, it has been common to express output energies in terms of edible tissue (Forster and Hardy, 2001; Troell et al., 2004; Tyedmers, 2000). This is not appropriate for this work, as the output from the hatcheries under consideration are smolts, not market sized fish. All energy efficiencies and energy ratios reported in this article are based on energy content of the whole fish (gross efficiencies).

The energy efficiency of the six options ranges from 0.97% for flow-through system with pumped supply to 3.49% for the flow-through system with gravity supply (Table 7). For these two systems, the ratio of Output Energy/Input Energy ranges from 29 MJ MJ^{-1} for FT-G option to 103 MJ MJ^{-1} for the FT-P option. Therefore, in the FT-P system, 103 MJ must be expended for every MJ of wet fish tissue produced.

Pitcher (1977) reported a gross efficiency of 11.6% for rainbow trout reared in a flow-through system. In this study, pumping energy, hauling of fish and feed, calcium carbonate, and indirect energy for feeds were not considered. When these components were deleted from the flow-through (FT-G) option, the energy efficiency increased from 3.49% to 12.0%.

The energy consumption and greenhouse gas emissions vary widely between different types of culture systems (this study) and between species (Troell et al., 2004). Luther et al. (2004) reported the following distribution of energy used in the entire U.S. food system:

On-farm production	18%
Processing and manufacturing	29%
Distribution	10%
In-home preparation	26%
Out-of-home preparation	17%

For each 1 MJ of power used on the farm, 4.6 MJ of power is used in processing, distribution, and final processing. Compared to average “food products”, salmon requires larger amount of processing, longer transportation distances, and refrigerated or frozen storage. This may increase the post-farm energy requirement compared to the data reported by Luther et al. (2004). The importance of reducing on-farms impacts must be judged in a wider context that includes the entire food production, processing, distribution, and final preparation chain.

5.4. Greenhouse gas emissions

The production of greenhouse gases (Table 6) is dominated by the contribution from energy (electrical and natural gas) and feed. The carbon dioxide emission of 26.7 g MJ^{-1} is based on the assumption of a 10% gas fueled generator and 90% hydropower mix (Appendix A, Table 2). While this value may be appropriate for the Pacific Northwest, reversing the proportion (90% gas fueled generator and 10% hydropower) would increase the emission factor to 184 g MJ^{-1} and increase the total emissions by 1.8 times for the PR system to 5.4 times for the FT-P system.

Tyedmers (2000) estimated that the greenhouse emissions from net pen rearing of Atlantic and coho salmon were 6.47 kg CO_2 (kg fish)$^{-1}$ and 8.02 kg CO_2 (kg fish)$^{-1}$, respectively. The values estimated for the six

Table 8
Ranking of rearing systems[a] based on different performance measures (see Table 7 for details)

Parameter	Ranking		
	Best	Second best	Worst
Water use	RU	PR-T	FT-P
Feed use	Little difference among systems		
Direct energy use	PR	RU	FT-P
Indirect energy use	FT-G	PR	FT-P
Total energy use	FT-G	PR	FT-P
Electrical/fuel energy use	FT-G	PR	PR-T
Land area	RU	PR, PR-T	FT-P
Solids discharged	RU	PR-T	FT-G
Total nitrogen discharged	RU	PR-T	FT-P, PO
Total phosphorus discharged	RU	PR-T	FT-P, PO
Total greenhouse gases	FT-G	PR	PR-T
Energy efficiency	FT-G	RU	FT-P

[a] Key to systems

FT-G	Flow-through with a gravity water supply
FT-P	Flow-through with a pumped water supply
PO	Flow-through with pure oxygen
PR	Partial reuse system
PR-T	Partial reuse with heating
RU	Reuse system

rearing options in this article were significantly higher (7 to 33 kg kg^{-1}; see Table 7). In contrast to this evaluation, Tyedmers (2000) did not consider the contribution from the fish's respiration. In addition, it is likely that the greenhouse emissions expressed in kg CO_2 (kg fish)$^{-1}$ are significantly larger for the freshwater rearing phase compared to net pen rearing because of the higher respiration rate of smaller fish.

5.5. Pollution discharges

The mass of solids discharged to the receiving water is lower for the reuse and partial reuse options as compared to flow-through and pure-oxygen options (Table 7). This is a result of (a) improved solids removal efficiencies (Table 2), (b) rapid removal of solids from the rearing units that results in reduced solubilization losses, and (c) lower discharge flows. The impact of the rearing options on nutrient discharges is relatively small (12% reduction for total nitrogen and 40% for total phosphorus).

5.6. Water consumption and space requirements

The flow-through system with gravity water supply (FT-P) has the largest water and space requirements while the reuse system (RU) has the smallest water and space requirements (Table 7). The water and space requirements for the six rearing options varies by a factor of 153 and 17 times, respectively. The large space requirement for the FT-P system is needed to avoid hydraulic interference among production wells which would reduce water yield. Much of this area would not appear to be used or occupied.

In contrast to conventional agriculture, water use in flow-through and reuse aquaculture systems is non-consumptive. Except for minor spillage and evaporation, all the water used is discharged back to a receiving body.

5.7. Impact of uncertainty in biological parameters

Values of key production parameters (G_c, feed conversion ratio (FCR), mortality, and maximum stocking density) were obtained from analysis of production records from the base case facility (FT-P) and these values were used for all the other rearing options. Production modeling depends very strongly on the values of these four key parameters. There is very little published data from commercial-sized facilities and much of what is available may be based on feeds, feeding tables, and rearing protocols no longer used. The largest uncertainty in these key production parameters is likely to be for the two 16 °C options (PR-T and RU). Over the temperature range of 5 to 20 °C, the value of G_c clusters around a value of 1.0 with no obvious dependence on temperature (Fig. 6, Iwama, 1996). A linear mortality assumption is unlikely to have a major impact on the production model results because of the relatively low green egg to smolt mortality of Atlantic salmon. Because of the increased capital and operating costs of the partial reuse and reuse systems, there is strong tendency to try to increase the maximum production density far beyond the 40 kg m^{-3} used in this work. Increasing rearing density is likely to have significant negative impacts on G_c, FCR, and mortality.

Information on pollutional loading parameters is sparse and it is commonly necessary to use data from several sources, species, and fish sizes. Comprehensive mass balances, solubilization rates, or atmospheric transfer rates are largely lacking for many important parameters, especially for actual production facilities. The energy density and greenhouse gas emission factors also depends strongly the source of the materials, how the materials are processed, and the specific energy sources used. More research is needed on these important topics.

6. Conclusions

Based on the information presented in Table 7, the ranking of the 6 production systems is graphically summarized in Table 8 for different performance measures. Based on simple prevalence, the FT-G, RU, and PR rank highest and FT-P ranks lowest. None of the rearing options perform better with respect to all the performance measures. The selection of the "best" system may require trade offs between the different performance measures. The ranking of the 6 production options in terms of capital and operating costs are likely to be quite different from those presented in this article.

Acknowledgements

We thank Dan Rotter of American Gold Seafoods LLC for his patience and assistance and John Forster and Anthonie Schuur for review of the earlier drafts of this manuscript.

Appendix A

Table 1
Energy density assumptions. (based on Brafield, 1985; Brown et al., 1985; Jonsson et al., 1997; Spreng, 1988; Tyedmers, 2000)

Component	Energy density (converted to fossil fuel equivalents)		
	Direct	Indirect	Transportation
Feed	22.38 MJ kg^{-1}	48.08 MJ kg^{-1}	2.015 MJ (MT km)$^{-1}$
Electricity	10.29 MJ (kw h)$^{-1}$	0.62 MJ (kw h)$^{-1}$ (6%)	N/A
Gasoline	32.25 MJ liter^{-1}	6.77 MJ liter^{-1} (21%)	N/A
Diesel	36.04 MJ liter^{-1}	7.56 MJ liter^{-1} (21%)	N/A
Natural Gas	0.03832 MJ liter^{-1}	0.00805 MJ liter^{-1} (21%)	N/A
Hydropower (on-site)	10.29 MJ (kw h)$^{-1}$	0.62 MJ (kw h)$^{-1}$ (6%)	N/A
Labor (FTE)	N/A	N/A	N/A
Steel	N/A	25 MJ kg^{-1}	N/A
Aluminum	N/A	140 MJ kg^{-1}	N/A
Fiberglass/Plastic	N/A	75 MJ kg^{-1}	N/A
Concrete	N/A	1 MJ kg^{-1}	N/A
Calcium Carbonate (oyster shell)	N/A	0.046 MJ kg^{-1}	2.015 MJ (MT km)$^{-1}$
LOX (liquid oxygen)	N/A	0.240 MJ kg^{-1}	2.015 MJ (MT km)$^{-1}$
Smolts	7.6 MJ (kg wet)$^{-1}$	N/A	2.015 MJ (MT km)$^{-1}$
Eggs	7.50 MJ kg wet)$^{-1}$	N/A	N/A

Table 2
Greenhouse gas assumption (based on Brown et al., 1985; Tyedmers, 2000)

Component	Equivalent CO_2 production
Feed (fish respiration)	Depends on system type and unit processes
Feed (manufacturing)	3330 g kg^{-1}
Hydroelectric	25 g $(kW\ h)^{-1}$
Natural gas fueled boiler	735 g $(kW\ h)^{-1}$
Electricity (10% gas and 90% hydro)	26.7 g MJ^{-1}
Gasoline	92.6 g MJ^{-1}
Diesel	87.9 g MJ^{-1}
Natural Gas/Propane	57.9 g MJ^{-1}
Hydropower (on-site)	N/A
Labor (FTE)	N/A
Steel	2500 g kg^{-1}
Aluminum	8000 g kg^{-1}
Fiberglass/Plastic	3000 g kg^{-1}
Concrete	150 g kg^{-1}
Calcium carbonate (oyster shell)	0.341 g kg^{-1}
LOX (liquid oxygen)	1.78 g kg^{-1}

References

Akvakulturdriftsforskriften 2004. Merknader til Forskrift 22. desember 2004 nr.1785 om drift av akvakulturanlegg (akvakulturdriftsforskriften) http://fiskeridir.no/fiskeridir/layout/set/print/content/view/full/4509.

Aubin, J., Papatryphon, E., Van der Werf, H.M.G., Petit, J., Morvan, Y.M., 2006. Characterisation of the environmental impact of a turbot (*Scophthalmus maximum*) re-circulating production system using Life Cycle Assessment. Aquaculture 261, 1259–1268.

Bergheim, A., Gaussen, M., Næss, A., Fjermedal, A.B., Hølland, P.M., Molværsmyr, A., 2002. Effects of oxygen deficit on post-smolt salmon. Trial 1. Rogaland Research. Report RF 2002/307. Norway, Stavanger. 25 pp.

Brafield, A.E., 1985. Laboratory studies of energy budgets. In: Tytler, P., Calow, P. (Eds.), Fish Energetics: New Perspectives. The Johns Hopkins University Press, Baltimore, pp. 257–307.

Brown, H.L., Hamel, B.B., Hedman, B.A., 1985. Energy Analysis of 108 Industrial Processes. Fairmont Press, Philadelphia. 314 pp.

Bureau, D.P., Cho, C.Y., 1999. Phosphorus utilization by rainbow trout(*Oncorhynchus mykiss*): estimation of dissolved phosphorus waste output. Aquaculture 179, 127–140.

Buryniuk, M., Petrell, R.J., Baldwin, S., Lo, K.V., 2006. Accumulation and natural disintegration of solid wastes caught on a screen suspended below a fish farm cage. Aquac. Eng. 35, 78–90.

Clark, E.R., Harman, J.P., Forster, J.R.M., 1985. Production of metabolic and waste products by intensively farmed rainbow trout, *Salmo gairdneri* Richardson. J. Fish Biol. 27, 381–393.

Collings, M.R., 1973. Generalization of stream–temperature data in Washington. Water Supply Paper 2029-B. U.S. Geological Survey, U.S. Printing Office, Washington, D.C.

Colt, J., 1991. Aquacultural production systems. J. Anim. Sci. 69, 4183–4192.

Colt, J., 2006. Water quality requirements for reuse systems. Aquac. Eng. 34, 143–156.

Colt, J., Watten, B., 1988. Applications of pure oxygen in fish culture. Aquac. Eng. 7, 397–441.

Colt, J., Orwicz, K., 1991. Modeling production capacity of aquatic culture systems under freshwater conditions. Aquac. Eng. 10, 1–29.

Colt, J., Tomasso, J., 2001. Hatchery water supply and treatment. In: Wedemeyer, G.A. (Ed.), Fish Hatchery Management, Second Edition. American Fisheries Society, Betheda, Maryland, pp. 91–186.

Colt, J., Lamoureux, J., Patterson, R., Rogers, G., 2006. Draft reporting standards for biofilter performance studies. Aquac. Eng. 34, 377–388.

Ellis, David W., Associates, 1996. Net Loss — the salmon netcage industry in British Columbia. A Report to the David Suzuki Foundation with Recommendations by The David Suzuki Foundation, David W. Ellis and The David Suzuki Foundation.

Fivelstad, S., Binde, M., 1994. Effects of reduced waterflow in softwater on Atlantic salmon smolts (*Salmo salar* L.) while maintaining oxygen at constant level by oxygenation of the inlet water. Aquac. Eng. 13, 211–238.

Fivelstad, S., Kallevik, H., Iversen, H.M., Møretrø, T., Våge, K., Binde, M., 1993. Sublethal effects of ammonia in soft water on Atlantic salmon smolts at a low temperature. Aquac. Int. 1, 157–169.

Fivelstad, S., Olsen, A.B., Kløften, H., Ski, H., Stefansson, S., 1999. Effects of carbon dioxide for Atlantic salmon (*Salmo salar* L.) smolts at constant pH in bicarbonate rich freshwater. Aquaculture 178, 171–187.

Fivelstad, S., Olsen, A.B., Åsgård, T., Bæverfjord, G., Rasmussen, T., Vindheim, T., Stefansson, S., 2003. Long-term sub-lethal effects of carbon dioxide on Atlantic salmon smolts: ion regulation, haematology, element composition, nephrocalcinosis and growth parameters. Aquaculture 215, 301–319.

Fivelstad, S., Olsen, A.B., Stefansson, S., Handeland, S., Waagbø, R., Kroglund, F., Colt, J., 2004. Lack of long-term sublethal effects of reduced freshwater pH alone on Atlantic salmon (*Salmo salar*) smolts subsequently transferred to seawater. Can. J. Fish. Aquat. Sci. 61, 511–518.

Folke, C., 1988. Energy economy of salmon aquaculture in the Baltic Sea. Environ. Manage. 12, 525–537.

Forsberg, O.I., 1994. Modeling oxygen consumption rates of post-smolt Atlantic salmon in commercial-scale land-based farms. Aquac. Int. 2, 180–196.

Forster, J., Hardy, R., 2001. Measuring efficiency in intensive aquaculture. World Aquac. 32(2), 41–42, 44–45.

Goldburg, R., Triplett, T., 1997. Murky Waters: Environmental Effects of Aquaculture in the US. Environmental Defense Fund, Washington, D.C.

Hosfeld, C.D., Engevik, A., Mollan, T., Lunde, T.M., Waagbø, R., Olsen, A.B., Breck, O., Stefansson, S., Fivelstad, S., 2008. Long-term, separate and combined, effects of environmental hypercapnia and hyperoxia in Atlantic salmon (*Salmo salar* L.) smolts. Aquaculture 280, 146–153. doi:10.1016/j.aquaculture.2008.05.009.

Iwama, G.K., 1996. Growth of salmonids. In: Pennell, W., Barton, B.A. (Eds.), Principles of Salmonid culture, Developments in Aquaculture and Fisheries Science, vol. 29. Elsevier, Amsterdam, pp. 467–515.

Jonsson, N., Jonsson, B., Hansen, L.P., 1997. Changes in proximate composition and estimates of energetic costs during upstream migration and spawning in Atlantic salmon *Salmo salar*. J. Anim. Ecol. 66, 425–436.

Knoph, M.B., 1992. Acute toxicity of ammonia to Atlantic salmon (*Salmo salar*) parr. Comp. Biochem. Physiol 101C, 275–282.

Kutty, M.N., 1968. Respiratory quotients in goldfish and rainbow trout. J. Fish. Res. Board Can. 25, 1689–1728.

Liao, P.B., 1971. Water requirements of salmonids. Prog. Fish-Cult. 33, 210–215.

Losordo, T.M., Rakocy, J.E., Masser, M.P., 1998. Recirculating aquaculture tank production systems — an overview of critical conditions. SRAC Publication No. 451. Southern Regional Aquaculture Center.

Luther, W., Suter, D.A., Brusewitz, G.H., 2004. Energy use in food processing. Food & Process Engineering Technology. American Society of Agricultural Engineers, St. Joseph, Michigan, pp. 285–291.

Mente, E., Pierce, G.J., Santos, M.B., Neofitou, C., 2006. Effects of feed and feeding in the culture of salmonids on marine aquatic environment: a synthesis for European aquaculture. Aquac. Int. 14, 499–522.

Mudrak, V.A., 1981. Guidelines for economical commercial fish hatchery wastewater treatment systems. In: Allen, L.J., Kinney, E.C. (Eds.), Proceedings of the Bio-Engineering Symposium for Fish Culture. Fish Culture Section, American Fisheries Society, Bethesda, pp. 174–182.

Naylor, R.L., Eagle, J., Smith, W.L., 2003. Salmon aquaculture in the Pacific Northwest — a global industry. Environment 45 (8), 18–39.

Patterson, M.G., 1993. Approaches to energy quality in energy analysis. Int. J. Glob. Energy Issues 5, 19–28.

Patterson, M.G., 1996. What is energy efficiency? Energy Policy 24, 377–390.

Pelletier, N., Tyedmers, P., 2007. Feeding farmed salmon: is organic better? Aquaculture 272, 399–416.

Pitcher, T.J., 1977. An energy budget for a rainbow trout farm. Environ. Conserv. 4, 59–65.

Smart, G.R., Knox, D., Harrison, J.G., Ralph, J.A., Richards, R.H., Cowey, C.B., 1979. Nephrocalcinosis in rainbow trout *Salmo gairdneri* Richardson; the effect of exposure to elevated CO_2 concentration. J. Fish Dis. 2, 279–289.

Spreng, D.T., 1988. Net-energy Analysis and the Energy Requirements of Energy Systems. Praeger, New York. 289 pp.

Summerfelt, S.T., Bebak-Williams, J., Tsukuda, S., 2001. Controlled systems: water reuse and recirculation. In: Wedemeyer, G. (Ed.), Fish Hatchery Management, 2nd edition. American Fisheries Society, Bethesda, Maryland, pp. 285–395.

Summerfelt, S.T., Davidson, J.W., Waldrop, T.B., Tsukuda, S.M., Bebak-Williams, J., 2004. A partial-reuse system for coldwater aquaculture. Aquac. Eng. 31, 157–181.

Timmons, M.B., Ebeling, J.M. 2006.The role of recirculating aquaculture systems (RAS) Part 1, Aquaculture Magazine, May/June 2006, 26–31.

Troell, M., Tyedmers, P., Kautsky, N., Ronnback, P., 2004. Aquaculture and energy use. Encyclopedia of Energy, vol. 1. Elsevier, Amsterdam, pp. 97–108.

Tucker Jr., J.W., 1998. Marine fish culture. Kluwer Academic Publishers, Boston. 750 pp.

Tyedmers, P.H., 2000. Salmon and sustainability: the biophysical cost of producing salmon through the commercial salmon fishery and the intensive salmon culture industry. Ph.D. thesis, University of British Columbia, 258 pp.

Tyedmers, P., Pelletier, N., Ayer, N., 2007. Biophysical Sustainability and Approaches to Marine Aquaculture Development in the United States — A Report to the Marine Aquaculture Task Force. School for Resource and Environmental Studies, Dalhousie University, Canada.

USEPA (United States Environmental Protection Agency), 1998. Detailed costing document for the centralized waste treatment industry. EPA 821-R-98-016. Office of Water, Washington, D.C.

Vinci, B.J., Summerfelt, S.T., Creaser, D.A., Gillette, K., 2004. Design of partial water reuse systems at White River National Fish Hatchery for the production of Atlantic salmon smolt for restoration stocking. Aquac. Eng. 32, 225–244.

Wagner, E.J., Bosakowski, T., Miller, S.A., 1994. Evaluation of the absorption efficiency of the low head oxygenation system. Aquac. Eng. 14, 49–57.

Wang, Y.B., Zhang, W.J., Li, W.F., Xu, Z.R., 2006. Acute toxicity of nitrite on tilapia (*Oreochromis niloticus*) at different external chloride concentrations. Fish Physiol. Biochem. 32, 49–54.

Watten, B.J., 1992. Modeling the effects of sequential rearing on the potential production of controlled environment fish-culture systems. Aquac. Eng. 11, 33–46.

Watten, B.J., Boyd, C.E., 1990. Gas transfer within a multi-stage packed column oxygen absorber: model development and application. Aquac. Eng. 9, 33–59.

WCED [World Commission on Environment and Development], 1987. Our Common Future. Oxford University Press, Oxford.

Willingham, W.T., Colt, J.E., Fava, J.A., Hillaby, B.A., Ho, C.L., Katz, M., Russo, R.C., Swanson, D.L., Thurston, R.V., 1979. Ammonia. In: Thurston, R.V., Russo, R.C., FetterolfJr. Jr., C.M., Edsall, T.A., BarberJr. Jr., Y.M. (Eds.), A Review of the EPA Red Book: Quality Criteria for Water, Water Quality Section. American Fisheries Society, Bethesda, Maryland, pp. 6–18.

Willoughby, H., 1968. A method for calculating carrying capacity of hatchery troughs and ponds. Prog. Fish-Cult. 30, 173–174.